Parity violation in hot QCD: How to detect it

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In a recent paper (hep-ph/0406125) Kharzeev argues for the possibility of *P*- and/or *CP*-violation effects in heavy-ion collisions, the effects that can manifest themselves via asymmetry in $\pi^{\pm}$ production with respect to the direction of the system angular momentum. Here we present an experimental observable that can be used to detect and measure the effects.

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The possibility of strong *P* and *CP* violation in heavy ion collisions was first proposed in Ref. [1]. Different experimental observables sensitive to the presence of *P*- and/or *CP*-odd domains in the deconfined QCD vacuum have already been discussed in the original papers and later in Refs. [2,3]. Remarkably, all the observables which have been discussed are related in smaller or larger extent to the anisotropic flow study efforts. In general, *P*- and *CP*-symmetry violation effects proposed in Ref. [1] manifest themselves via a nonstatistical difference of the reaction planes reconstructed using different groups of particles, either of different charge or in different kinematic regions. In symmetric nuclear collisions (the only ones discussed in this paper) there should be only one plane of symmetry, and therefore any observation of the opposite would mean *P*- and/or *CP*-violation effects. Interestingly, many of the "symmetry sensitive" quantities are routinely calculated in flow analyses for "quality assurance" purposes (checking analysis consistency). No deviation from expectations based on symmetry with respect to the reaction plane has been observed so far.

However, Refs. [1–3] do not discuss one important case, namely, the possibility of preferential emission of particle/antiparticle, e.g., $\pi^{\pm}$, into opposite sides of the reaction plane. This happens to be exactly the observable signal of the *P*- and *CP*-breaking mechanism discussed by Kharzeev in his recent preprint [4]. Kharzeev argues that due to the parity violating interactions, the asymmetry in pion production along the direction of the system angular momentum (perpendicular to the reaction plane) could be as high as of the order of one percent in midcentral Au+Au collisions at RHIC. The orientation of the asymmetry (parallel or antiparallel to the direction of the angular momentum) can change from event to event, and therefore the effect can be detected only by correlation study.

In this paper we propose to use for that purpose a technique that is well known in anisotropic flow analysis and usually referred to as mixed harmonics technique [5] or three particle correlations [6]. The essence of this technique is in the isolation of correlations related to a given direction. Suppose that positive pions are emitted preferentially in the positive *y* direction (along the angular momentum). The azimuthal distribution in this case can be written as $dN/d\phi \propto [1+2a\sin(\phi)]$, where ϕ is the particle emission azimuthal angle relative to the reaction plane (Ψ_{RP}), and the parameter *a* can be directly related to the asymmetry in pion production presented in Ref. [4]: $A_{\pi^+}=\pi a/4 \approx Q/N_{\pi^+}$. In the latter expression *Q* is the topological charge $(Q \geqslant 1)$ and N_{π^+} is the pion multiplicity in about one unit of rapidity [4]. For midcentral Au+Au collisions at RHIC $N_{\pi^+} \sim 100$ and these estimates yield a low limit on *a* of the order of one percent. Let us consider azimuthal correlation between particles *a* and *b* by evaluating the quantity

$$\langle \cos(\phi_a-\Psi_2)\cos(\phi_b-\Psi_2) - \sin(\phi_a-\Psi_2)\sin(\phi_b-\Psi_2)\rangle \\ = \langle \cos(\phi_a+\phi_b-2\Psi_2)\rangle = (v_{1,a}v_{1,b}-a_a a_b)\langle \cos(2\Psi_2)\rangle, \tag{1}$$

where the average is taken over events, Ψ_2 is the second harmonic event plane, $\langle \cos(\Psi_2-\Psi_{\mathrm{RP}})\rangle$ is the so-called event plane resolution (how well on average one reconstructs the reaction plane from elliptic flow; for details see Ref. [5]). The final expression reflects the correlations along the two axes, one in the reaction plane [directed flow, characterized by $\langle \cos(\phi-\Psi_{\mathrm{RP}})\rangle \equiv v_1$] and perpendicular to the reaction plane—the manifestation of symmetry breaking discussed in Ref. [4]. All other correlations, as they are not sensitive to the orientation of the reaction plane, cancel out (for the systematic uncertainty in this statement see Refs. [6,7] and the discussion below). The proportionality to the reaction plane resolution reflects a decrease in correlations due to finite ability to resolve the true reaction plane orientation. If only one particle is used to determine the event plane the equation reduces to

$$\langle \cos(\phi_a+\phi_b-2\phi_c)\rangle = (v_{1,a}v_{1,b}-a_a a_b)v_{2,c}, \tag{2}$$

where the typical values of the parameter $v_{2,c}$, elliptic flow of particle of type *c*, is of the order of 0.04–0.05 for midcentral collisions. Equations (1) and (2) are usually employed for directed flow study [5–7]. The main advantage of these observables is their sensitivity to correlations in particle production along a given direction. As already discussed above, these observables represent the difference in correlations along the *x* and *y* axes, therefore any correlations that do not depend on the orientation with respect to the reaction plane cancel out. If directed flow is zero, the above observables present a direct measure of the symmetry violation effects. In relativistic heavy ion collision, the condition of $v_1=0$ can be achieved by studying the correlations in the rapidity region symmetric with respect to the midrapidity, such that the average directed flow equals zero. As discussed in detail, for example, in Ref. [6], using this technique one is able to measure the correlations, v_1 or asymmetry parameter $a_{\pi^\pm}$ in our case, with an accuracy at a sub-percent level.

Note the possibility of measuring the correlations using different charge combinations: $\pi^+\pi^+$ and $\pi^-\pi^-$ correlations should be negative, while $\pi^+\pi^-$ to be positive, and all three to be of the same magnitude. These relations provide an additional cross check of the results if observed.

The main systematic uncertainty in three particle correlation measurements is due to processes when particles a and b are products of a resonance decay, and the resonance itself exhibits elliptic flow [6,7]. Keeping only this contribution one can write

$$\langle\cos(\phi_a + \phi_b - 2\phi_c)\rangle = \langle\cos[(\phi_a + \phi_b - 2\phi_{\rm res}) + 2(\phi_{\rm res} - \phi_c)]\rangle \approx \frac{f_{\rm res}\langle\cos(\phi_a + \phi_b - 2\phi_{\rm res})\rangle v_{2,\rm res}}{N_\pi} v_{2,c}, \tag{3}$$

where $f_{\rm res}$ is the fraction of pion pairs originating from resonance decays (should be relatively small for the same charge combinations), $\langle\cos(\phi_a+\phi_b-2\phi_{\rm res})\rangle$ can be considered as a measure of the azimuthal correlations of decay products with respect to the resonance azimuth, and $v_{2,\rm res}$ is the resonance elliptic flow. The factor $1/N_\pi$ reflects the probability that both pions in the pair are from the same resonance. Considering an estimate of such contribution note that $\langle\cos(\phi_a+\phi_b-2\phi_{\rm res})\rangle$ is zero if the resonance is at rest, and becomes nonzero only due to resonance motion. More accurate estimate could be done with proper simulations of such effects, but the total contribution should be smaller than $\langle\cos(\phi_a+\phi_b-2\phi_c)\rangle \leqslant 10^{-3}\, v_{2,\rm res} v_{2_c}$, where the factor 10^{-3} is coming from the estimates of nonflow azimuthal correlations [7]. Taking all together, one finds the systematic uncertainty in measurements of a_π parameter below one percent level.

In summary, we propose to use mixed harmonics (three particle) azimuthal correlations to detect strong symmetry violation effects in heavy ion collisions. Our estimates of the systematic uncertainties indicate that the measurements of the asymmetry in pion production with respect to the system angular momentum can be performed at a level better than one percent (about the lower limit of the effect as predicted by theory), and probably much better with an additional study and simulations of the effects contributing to the systematic uncertainty.

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